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Simulation analysis on structure safety of two typical refuge chamber shell forms under explosion load

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Abstract

In order to reduce the risk of sealing and improve the structural strength safety for coal mine mobile refuge chamber, two models with certain proportion were set up after mechanical analysis. One was one-piece coal mine mobiles refuge chamber form which involves less sealing problems between sections, the other was segmented coal mine mobiles refuge chamber form which is easy to transport. A simulation analysis method was used to confirm their structure safety. Verified finite element analysis method was used to simulate the responses under blast loading. Considering the harsh conditions, the maximum pressure of the triangle impact load was 0.8MPa, and the pulse width was 300ms. The maximum stress of one-piece one is less than segmented one. It demonstrated that section connecting position can cause more stress concentration. The maximum displacement one of one-piece is more than segmented one. It demonstrated that segmented type had lower displacement. Weak part of one-piece was middle position of front and back end shell. Weak parts of segmented type were middle position of sides and section connecting position. Based on their weak places analyzed, suggestions were put forward for the two kinds. Arc structure might be used in the front and back end shell. The front and back end shell might be thickened. Only inclined shaft with larger wellhead is suitable for this type. Segmented type could be used in large or medium-sized one.

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Keywords: deep shaft; refuge chamber; shell structure; structure safety analysis; shock wave; FEA

Nomenclature

q	distributed load (kN/m)
E	elastic modulus of steel (N/mm^2)
I	interface inertia matrix of steel (mm^4)
l	length of the beam (mm)
δ(t)	displacement of nodes on the elastomeric matrix
P(t)	a unit nodal load matrix
K	the total stiffness matrix
M	the total mass matrix
C	the total damping matrix.

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1. Introduction

1.1. Magnitude of problem

As one of five mine nature disasters, mine gas explosion brought heavy casualties and great loss each year in China. Miners were not able to evacuate after accidents due to many kinds of risk, such as oxygen depletion near explosion area, high-temperature smoke or high concentrations poisonous gases and so on[1]. State Administration of Work Safety[2] indicated that the percent of miners killed due to those reasons was about 80%. Besides, about 75% mine gas explosion death was caused by the toxic and harmful gas. Because the concentration of carbon monoxide can reach 1%-4%, the highest even 7%-8%[3], it may be the most harmful kind of gas in the explosion.

In most cases, people cannot bear the explosion pressure. The shock wave might cause impact hurt, visceral injury, mechanical hurt. Coal mine refuge chamber is able to isolate toxic and harmful gas and shock wave from outside. So it can provide emergency airtight place which could meet basic survival conditions. The using of coal mine underground emergency system including refuge chamber had been detailed provided in Coal Mine Emergency Management System Construction Interim Provision. That could improve coal mine emergency ability, thus reduce accident casualties to promote coal mine safety. Coal mine mobile refuge chamber can be moved with coal mining activity places, so this type would be widely put into use.

During accidents, there is great impact load and stress is put on the refuge chamber. That can result in certain degree of plastic deformation of structure. When dumping and distortions take place, the structure would be serious damaged and lose protection. Therefore, it should have enough impact resistance strength.

1.2. Past Research efforts

In earlier study, key technology[4-5] and design methodology[6], heat-shielding performance[7], views about the physical discomforts and psychological stresses[8] for refuge chamber capsule had been mature. Ming Song et al.[9] investigated buckling capacity optimization of coal mine refuge chamber's shell under uniform axial compression. L.D. Ma et al.[10] also proved that there is obvious relationship between the ability of refuge chamber under axial impact load and the thickness, depth of flat spherical shells. These works might be helpful. But there is less structure safety analysis for it under explosion load. For further study, Zhao Huanjuan et al.[11] used explicit nonlinear dynamic analysis program to indicate segmented type would not be damaged when explosion suddenly happened.

Segmented type has high impact resistance. However, as assembled with basic segments, it must have qualified sealing to ensure its protective performance. More cost is needed to reduce risk of sealing. Strong shock wave possibly leads to plastic deformation. The temperature is about 2000℃ when explosion happened, and decreases to about 1000℃ after spreading 5m. The sealing is easy to damage if the temperature resistance is not good enough. So, high airtight performance and mechanical properties should be required. This segmented structure is similar to large thin-walled sealing capsule, which requires high quality sealing factors such as surface roughness and flatness of sealing surface and grooves[12]. So, high cost manufacturing process should be used on the purpose of controlling the deformation.

From above, sealing risk should be avoided as much as possible. Jiao Jian et al.[13] had solved doors sealing problem. One-piece coal mine mobile refuge chamber adopts overall mechanical structure, While segmented type is easy to transport.

Therefore, two structure forms would be designed according to the applicable condition of them. One is for one-piece type, the other for segmented type. Further improved simulation calculation for the two forms under explosion load should be done. Finite element analysis would be used to analyze the stress and deformation. The maximum stress and plastic deformation would be found out to determine whether the structure forms are damaged. Weak parts would be found out. Based on analysis, further improvements could be put out.

2. Methods

2.1. Design

Coal mine refuge chambers could be divided into one-piece type, segmented type, and others from their mechanical structure characteristics. Segmented type is a combination of segments while one-piece type is only one whole segment mechanical structure.

There was impact load loaded in the refuge chamber sides except bottom one. Each side could be simplified as simply supported beam. The simply supported beam was clamped beam under distributed load. The force diagram of simply

supported beam is shown in figure 1. One-piece type could be simplified as beam without support while segmented type as beam with support. The maximum deflection equation of this beam can be written as Eq. (1).

$$f = \frac{-(5ql^4)}{384EI} \tag{1}$$

where q is distributed load, kN/m; E is elastic modulus of steel, N/mm^2; I is interface inertia matrix of steel, mm^4; l is length of the beam, mm.

Midway deflection of one-piece type might be more than segmented type with same size. Hence, there might be bigger deflection in explosion which possibly brings damage and affects the sealing. Therefore the structure should be carefully designed to meet the safety requirement with the possible lighter weight.

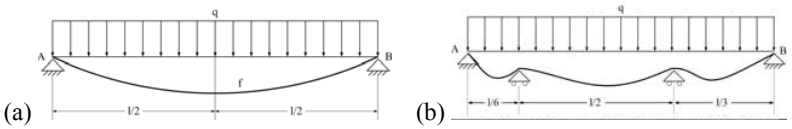

Fig. 1. Force diagram of simply supported beam (a) beam without support (b) beam with support.

So, the length of one-piece type should be cut short while effective volume was assured, whereupon deflection in middle would be decreased. Different than from that way, reinforcing rib was welded on the shell surface to reinforce flexural rigidity. The structure forms are shown in figure 2. The material[14] kinds and thickness of parts are shown in table 1. Material characteristic parameters are shown in table 2.

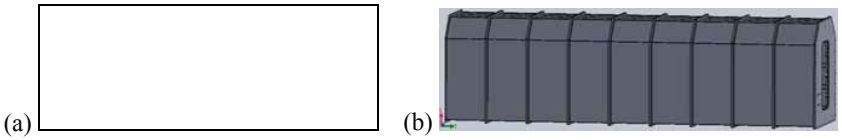

Fig. 2. Geometry constructional of refuge chambers (a) one-piece type (b) segmented type

Table 1. Material kinds and thickness of the refuge chamber parts

Parts	Material	Thickness /mm
Shell	Q345	12
Reinforcing rib	Q345	8

Table 2. Material characteristic parameter

Material	Q345
Density/ g (cm)$^{-3}$	7.85
Modulus of elasticity/ GPa	206
Poisson's ratio	0.3
Yield value of stress / MPa	345
Tensile strength / MPa	510~660

2.2. Basic assumption and equations

As the structure was mainly connected by welding and bolted connections, there were no relative motion parts, so hypothesis was determined: the welding of structural parts is completely reliable. There was no penetration between structural parts. All stress of welding was eliminated. There is no deformation about manufacture or installation. Bolted connection is reliable. There is no effect produced by pre-stressed of bolted connection.

Explicit nonlinear dynamic analysis program LS-DYNA was used to calculate stress and elastic-plastic deformation. The fundamental equation for this dynamic problem can be written as follows.

$$M\frac{d^2\delta}{dt^2}+C\ \frac{d\delta}{dt}+K\delta\ (\mathrm{t})\ =P\ (t) \tag{2}$$

where δ(t) is the displacement of nodes on the elastomeric matrix; P(t) is a unit nodal load matrix; K is the total stiffness matrix; M is the total mass matrix; C is the total damping matrix.

For the dynamic structure, stress and displacement is a function of time, strain and stress equation in unit can be written as follows.

$$M\frac{d^2\delta}{dt^2}+C\ \frac{d\delta}{dt}+K\delta\ (\mathrm{t})\ =P\ (t) \tag{3}$$

$$\sigma(t)=D\varepsilon(t)=DB\delta(t)^e \tag{4}$$

where ε(t) is the strain in unit; σ(t) is stress in unit; δ(t)e is displacement vector in unit nodal; B is the strain matrix; and D is the elastic matrix.

2.3. Simulation model building

The same blast load was loaded on five-sides. 2.0 was taken as safety coefficient. Calculated maximum was 0.8 MPa. Pulse width was 300ms. The pressure-time curve for triangle impact load is shown in figure 3. Bottom of the refuge chamber should be fixed at bottom plate, so constraint was simplified to fixed constraints.

Considering actual thickness of shell and need of compute numeration, SHELL163 element was used to partition shell and reinforcing rib. SOLID164 element was used to partition cabin doors. The spring-damper element was used to partition threaded connection. The biggest element size of shell element was set to 50. The biggest of solid element was set to 25. Important parts need further perfect partition to reduce error between simulation response and actual result. The biggest of important parts was set to 15.

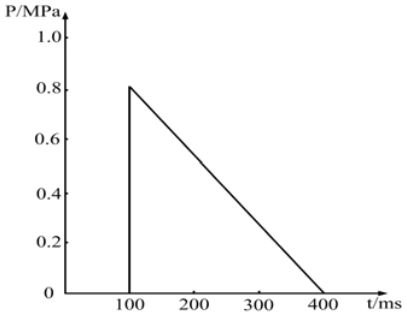

Fig. 3. Pressure-time curve of shock wave

3. Results and discussion

3.1. Results

(1) Stress results.

The remarkable stress results were extracted, as shown in figure 4. In the cloud, red represented the maximum while blue represented the minimum. During impact process, the maximum of one-piece type appeared at chamfering position, but segmented type appeared at section connecting position and chamfering position. The maximum of one-piece type was 357.1 MPa while segmented type was 375.1 MPa, and both occurred at many times such as 210 ms. Stress of few elements exceeded the material yield strength, but did not exceed tensile strength.

The clouds show that $\sigma_{one\text{-}piece}<\sigma_{segmented}$. It demonstrated that section connecting position can cause more stress concentration. Once it exceeds tensile strength, sill risk might be caused.

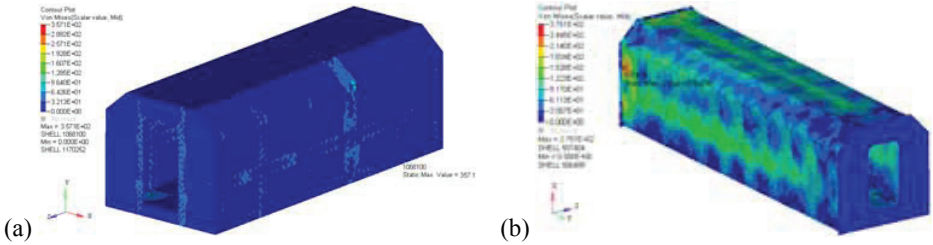

Fig. 4. Stress cloud chart for refuge chambers in 350 ms (a) one-piece type (b) segmented type.

(2) Displacement results.

The remarkable displacement results were extracted, as shown in figure 5. In the cloud, red represented the maximum while blue represented the minimum. The maximum of one-piece type appeared at middle position of front and back end shell but the segmented type appeared at middle position of sides. The maximum of one-piece type was 18.696 mm while the segmented type was 14.44mm and both appeared at many times such as 210 ms. Visibly, reinforcing rib strengthened shell. They could meet rigidity requirement.

The clouds show that $\delta_{one\text{-}piece}>\delta_{segmented}$. It demonstrated that segmented type had lower displacement. Finally, one-piece type should not have large size.

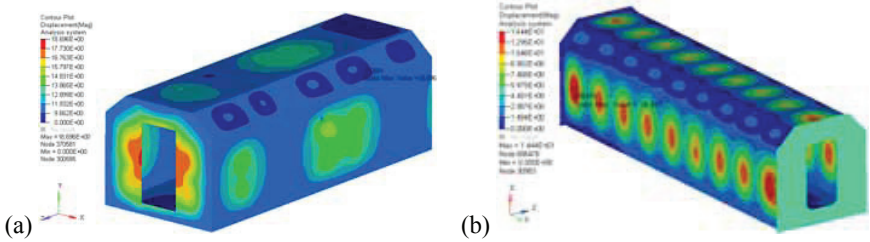

Fig. 5. Displacement cloud chart for refuge chambers in 350 ms (a) one-piece type (b) segmented type.

3.2. Results analysis

Numerical simulation results were extracted, as shown in table 3. The places maximum appeared could be clearly found out. Stress concentration would be abated. Larger inner diameter round corner should be used to improve chamfering angles. Then, strength of this refuge chamber could be strengthened.

Table 3. Numerical simulation results

Refuge chamber type	The maximum stress	The maximum displacement
One-piece type	357.1 MPa, chamfering position.	18.696mm, middle position of front and back end shell.
Segmented type	375.1 MPa, section connecting position and chamfering position.	14.44 mm, middle position of sides.

It can be seen from the above analysis.

(1) Weak positions of one-piece model were middle parts of front and back end shell. Flexural rigidity must be increased to enhance impact resistance. This one-piece model had solved strength security problems and cut down risk of sealing between segments. But the dimensional requirement is high. Wellhead of small size mine is difficult to meet the requirements. Only inclined shaft with larger wellhead is suitable for this type.

(2) Weak parts of segmented model were middle position of sides and section connecting position. For a same refuge chamber, the smaller section, then it would come with bigger displacement and lower stress. Consider size of segmented one, appropriate section should be designed. Segmented type could be used in large or medium-sized one.

(3) There were two methods for optimizing. One was arc structure should be used in the front and back end shell. It could buffer outside pressure. This method was excellent. It would not bring too weight. However, this method requires high technology. Another one was to thicken the end shell or weld reinforcing rib on the end. Rectangular tube and flat steel would be chose for the mechanical characteristics. Rectangular tube could be welded in external shell while flat steel in internal shell.

4. Conclusions

Firstly, two models for one-piece coal mine mobiles refuge chamber and segmented coal mine mobiles refuge chamber with certain proportion were set up after mechanical analysis. They met with volume requirements. This one-piece type did not involve sealing problems between segments. Segmented type is easy to transport.

Secondly, a simulation analysis method was used to confirm their structure safety. Verified finite element analysis method was used to simulate the responses under blast loading. The maximum pressure of the triangle impact load was 0.8MPa, and the pulse width was 300ms. The maximum stress of one-piece one is less than segmented one. It demonstrated that section connecting position can cause more stress concentration. The maximum displacement one of one-piece is more than segmented one. It demonstrated that segmented type had lower displacement.

Finally, based on their weak places analyzed, suggestions were put forward for the two kinds. Arc structure might be used in the front and back end shell. The front and back end shell might be thickened. Only inclined shaft with larger wellhead is suitable for this type. Segmented type could be used in large or medium-sized one.

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